Lec (11)

Lattice matched Hetero structure :

Strained layer Epitaxy :

atoms of grown laye adjust themselves to be matched with atoms of substrate

Condition : thickness of grown layer $< d_c$

$$d_c = \frac{a_s}{2|\epsilon|} \qquad \epsilon = \frac{a_L - a_s}{a_L}$$

↓

missmatch material

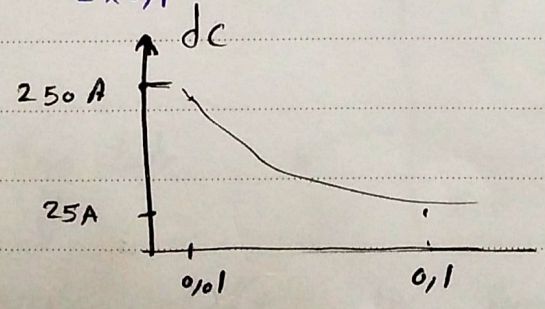
Ex :

$\epsilon = 0,01 \qquad a_s = 5A^\circ$

$$d_c = \frac{5}{2 * 0,01} = 250A$$

Ex $\epsilon = 0,1 \qquad a_s = 5A \qquad a_L = \frac{5}{0,9} A^\circ$

$$d_c = \frac{5}{2 * 0,1} = 25\ A^\circ$$



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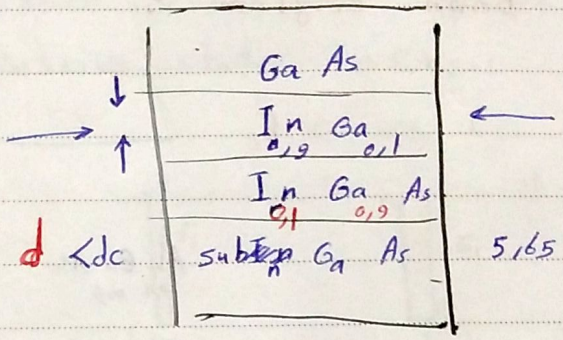
EX: $In_x Ga_{1-x} As$ / GaAs

X = 0 GaAs a = 5,65 A°

X = 1 InAs a = 5,87 A°

Bult in strain



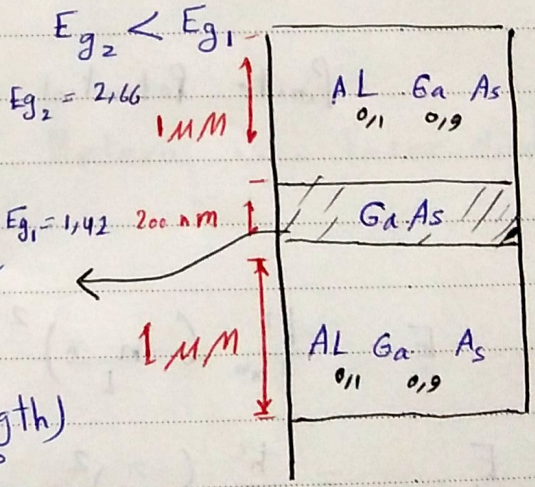
Double Hetero structure:

tow semiconductor material grown in to a sandwich

type1 outer layer → material has E_{g_1}

The sandwich layer has $E_{g_2} < E_{g_1}$

EX: $Al_x Ga_{1-x} As$ / GaAs



Thikness $d < \Lambda$ (deBrogli wave length)

electron wavelength

$\Lambda = \frac{2\pi}{k}$ $k = \frac{P}{\hbar}$

$E_{k.E} = \frac{1}{2} m v^2 \cdot \frac{m}{m}$ $E_{KE} = \frac{1}{2} \frac{(mv)^2}{m} = \frac{P^2}{2m^*}$

$\Rightarrow P = \sqrt{2 m^* E_{KE}} = \hbar k$

E_{KE} thermal energy | $T = 300\ k^\circ$ = 0,025 eV

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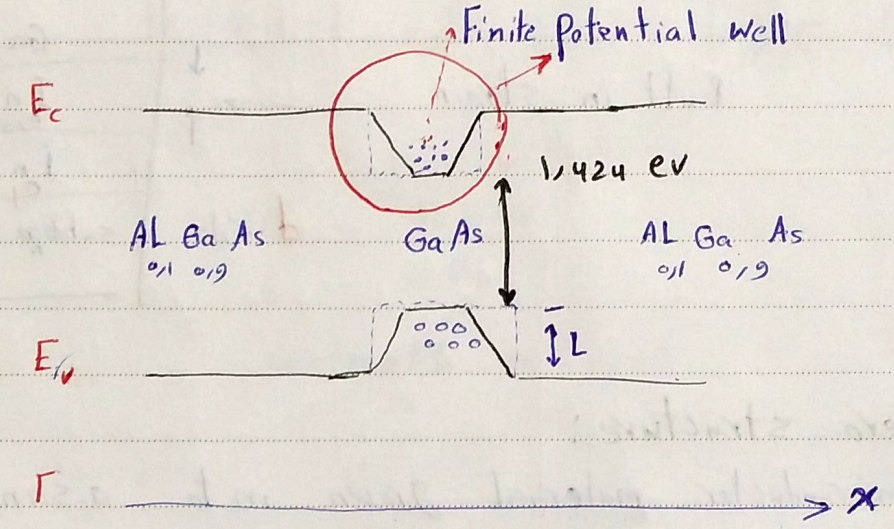
$m_c^* = 0{,}067\, m_0 = 0{,}067 \times 9{,}1 \times 10^{-31}$

$\Lambda = 300\ A^\circ$

$* \Rightarrow$ to convert to quantum well structure from bulk material

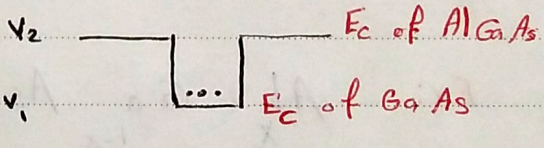
$\Rightarrow d_L < (\lambda_e)\,\Lambda$

Band diagram : electron in a box



$E_g|_{x=0,1} = 1{,}424 + 1{,}247\,x = 1{,}55\ eV \qquad x < 0{,}45$

Finite Potential Well (finite quantum well)



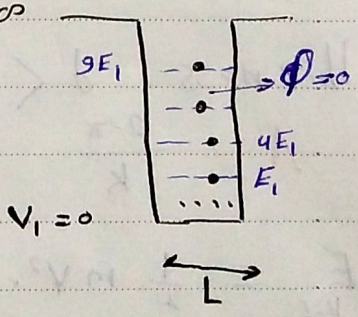
in finite Potential

$E = \frac{-\hbar^2}{2m^*}\left(-\frac{n\pi}{L}\right)^2$

$n = 1, 2, 3 \ldots$

$E_{n=1} = \frac{\hbar^2}{2m^*}\left(\frac{\pi}{L}\right)^2$

$E_{n=2} = 4E_1$



$L\uparrow \Rightarrow E\downarrow$

$L\downarrow \Rightarrow E\uparrow$

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finite Potential well :

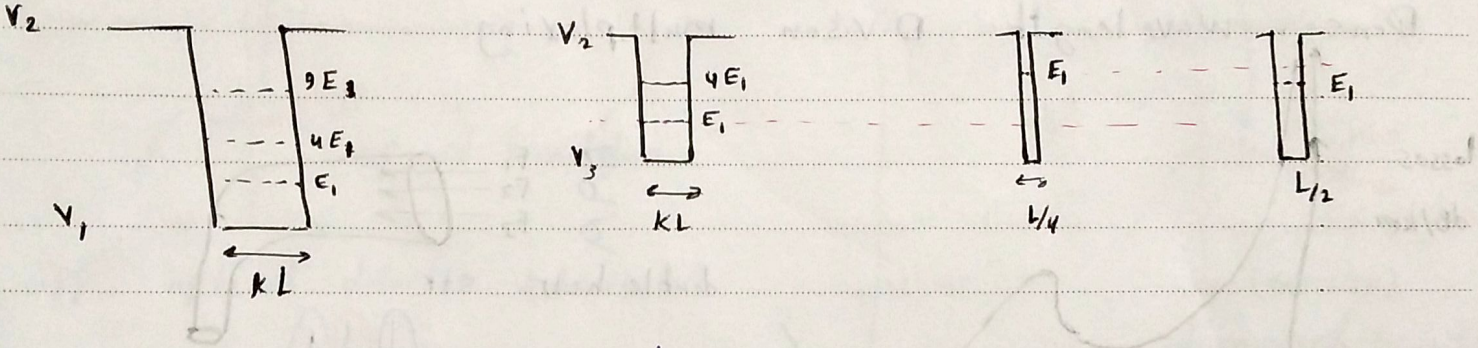
$E_{c_2} > E_n > E_{c_1}$

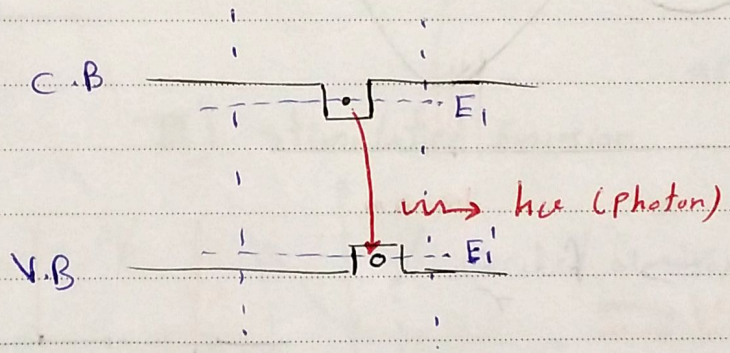
As L (thickness of active material)

Q4 sheet (4)

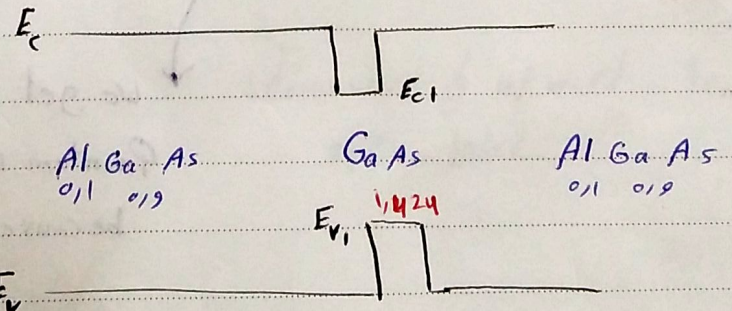
the thickness (L)

* decreas' ⟹ E_1 the first state in the well shift up & distance between successive state increas





The application of Double Hetero is laser diod



$E_{c_1} = 0,67\ E_g'$

$E_{v_1} = 0,33\ E_g'$

$\left(E_{g\ Al\ Ga\ As}' - E_{g\ Ga\ As} \right)$

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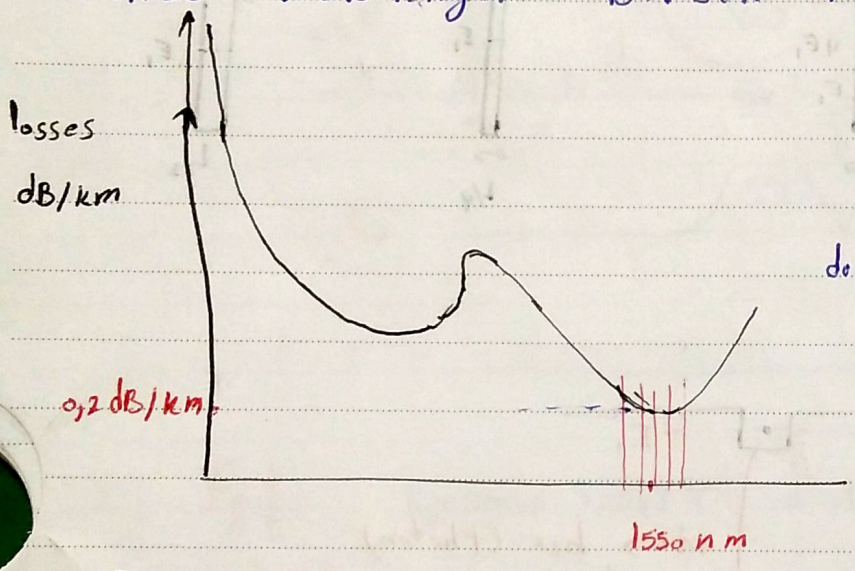
$E_g = 1,55 - 1,424 = 0,126$

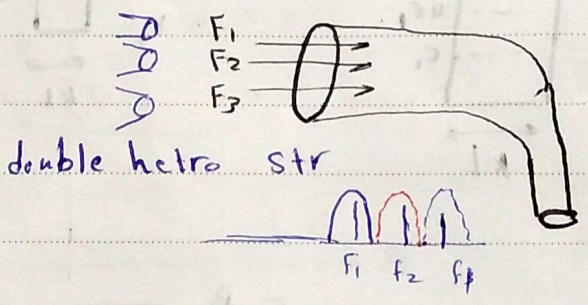
$E_{c_1} = (0,67 \times 0,126) + 1,55$

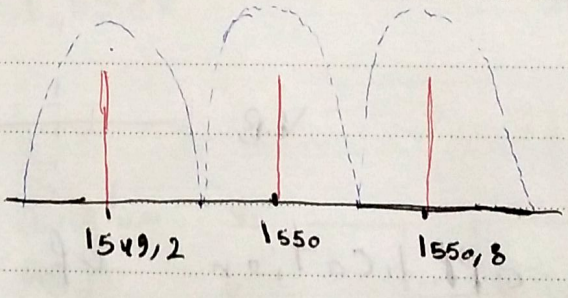
$E_{v_1} = 1,424 - 0,33 \times 0,126$

objective: Quantum well (optical Communication)

Dense wavelength Divison multiplexing







$0,8$ nm ⟶ 100 GHz

$f = \frac{c}{\lambda} \Rightarrow f = \frac{c}{r}$

$\frac{\partial f}{\partial r} = \frac{c}{r^2}$

$df = \frac{c}{r^2} \cdot dr$

df → 100 GHz

r → 1550 nm

we get it by using Quantum well structure because of low value

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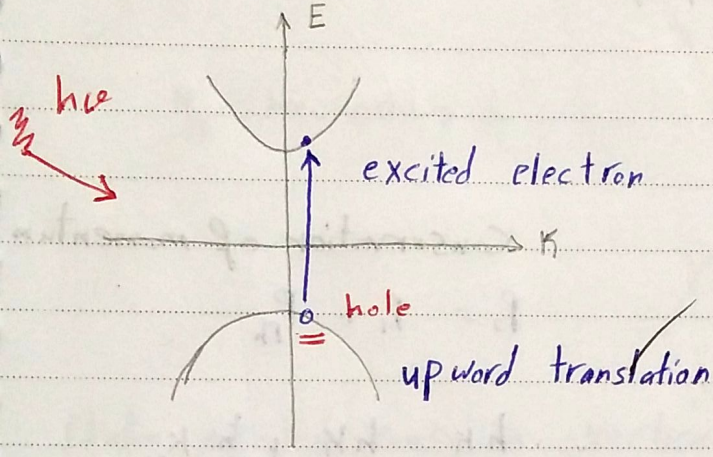
Lec (12)

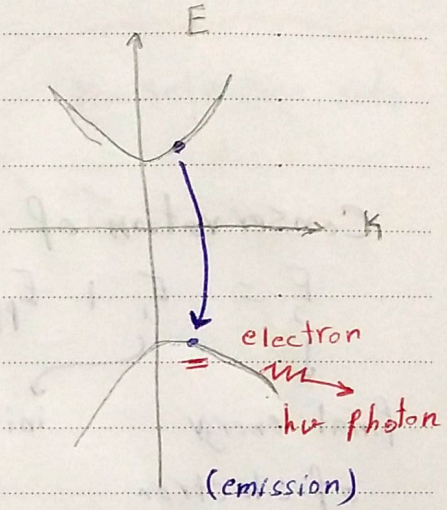
interaction of ligh with matter

I) - Absorption



app: optical detector (absorption)

II) spontaneous Emission

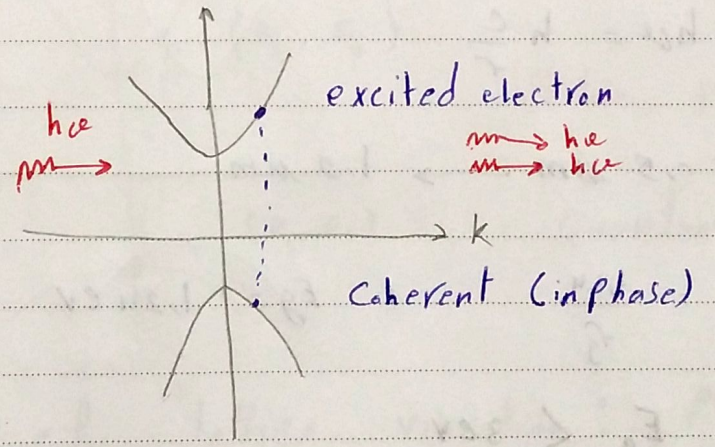


(emission)

downword transition

app: LED

III) stimulated Emission



downword & upword transation

app: Laser

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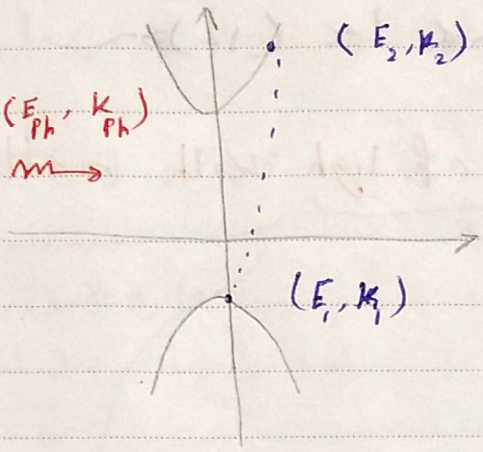
transition :



Conservation of energy

$$E_2 = E_1 + E_{Ph}$$

E_2: final energy of electron

E_1: initiale energy of electron

Conservation of momentum

$$P_2 = P_1 + P_{Ph}$$

$$\hbar K_2 = \hbar K_1 + \hbar K_{Ph}$$

$$K_2 = K_1 + K_{Ph}$$

K_2: e

K_1: Cs material

K_{Ph}: Ph

$$E_{Ph} = h\nu = h\frac{c}{\lambda}$$

$\lambda = 0{,}5\ \mu m \longrightarrow 1{,}5\ \mu m$

$$E_g = \frac{1{,}24}{\lambda_g} \quad / \quad E_g = 1{,}24\ ev$$

$1\ ev < E_g < 3\ ev$

energy of Photon Can allow transition in semi conductor material

$$K_2 = K_1 + K_{Ph}$$

electron wave vector

$$\frac{2\pi}{100\,A^\circ} = \frac{2\pi}{1} \times 10^8$$

Photon wave Vector

$$\frac{2\pi}{1 \times 10^{-6}\ \mu m} = 2\pi \times 10^6\ m^{-1}$$

$$\left(K = \frac{2\pi}{\lambda\ A^\circ}\right)$$

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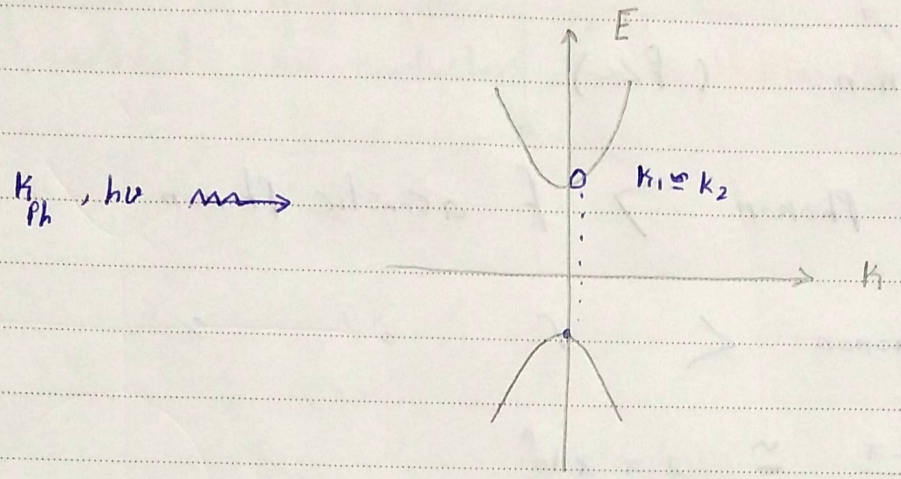
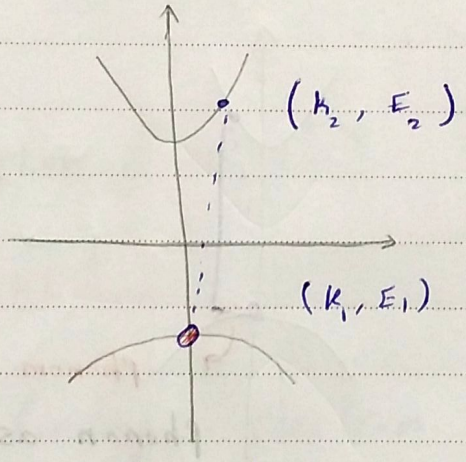
$\Rightarrow$ $k_2 - k_1 \simeq 0$ momentum of photon in neglected w.r.t momentum of electron



k- selection rate
$\Delta k = 0$

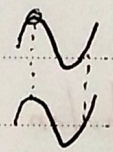
Photon Assisted transition = Vertical transition

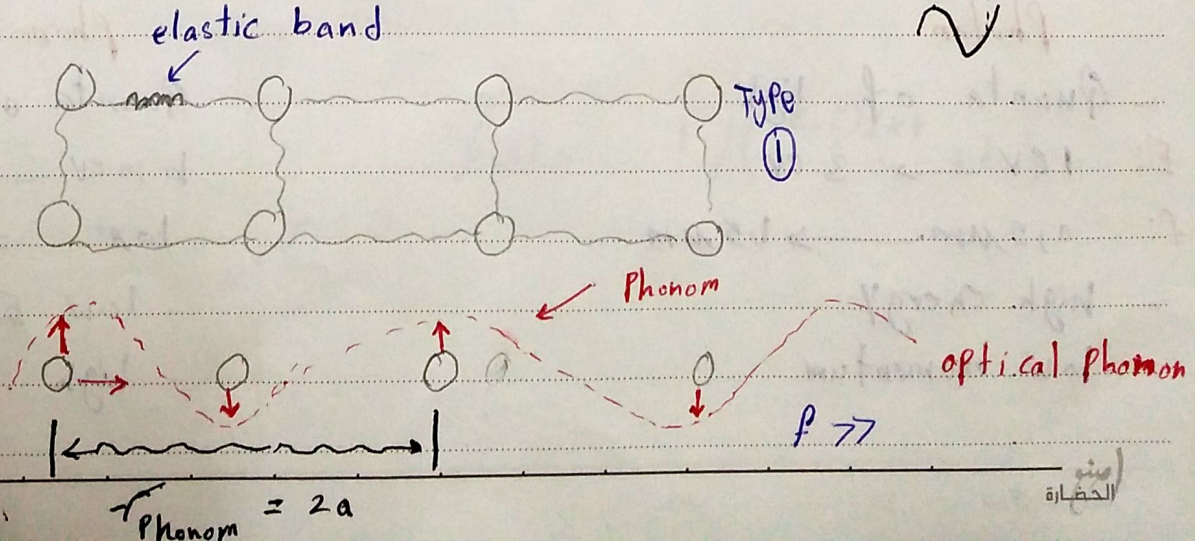
oblique transition :



(Photon , Phonom)
↓
Quantum of ligh

Phonom Quantum of lattice vibration :





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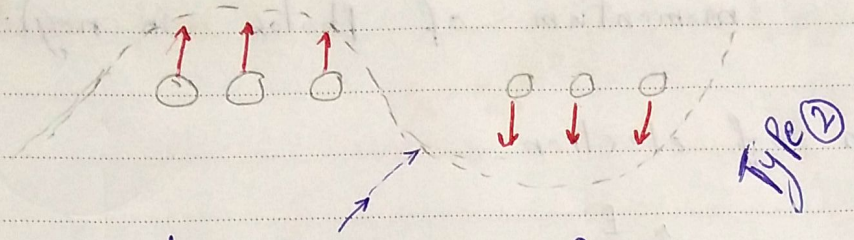


Type ②

Acoustic Phonon ($f \ll$)

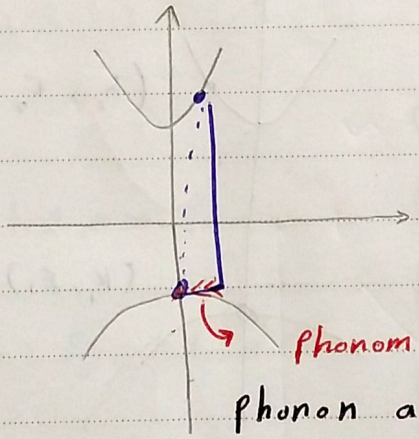
frequency of Phonon $>$ f acoustic Phonon

f optical Phonon $<$ f " "

$$K = \frac{2\pi}{\lambda_{Phonon}} \simeq \frac{2\pi}{10A^\circ} \simeq 2\pi \times 10^9$$

Energy of Phonon = small

= 10 mev $\longrightarrow$ 70 mev $\cong$ thermal Energy



$\Longrightarrow$ (Photon , Phonon)

Phonon assisted transition

Photon

- Quanta of ligh

E: 1 eV $\longrightarrow$ 3 eV

λ: 0,5 μm $\longrightarrow$ 1,5 μm

- high energy
- low momentum

Phonon

Quanta of lattic vibration

10 mev $\longrightarrow$ 70 mev

10 A° $\longrightarrow$ 100 A°

low Energy

high momentum

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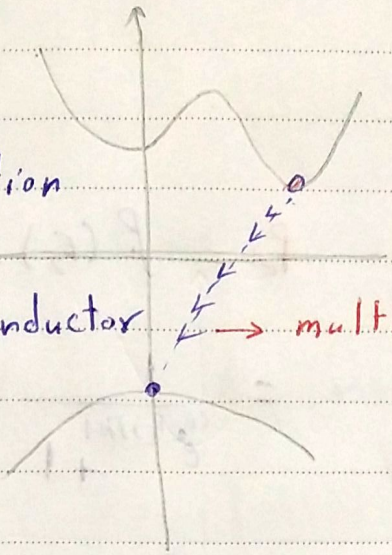
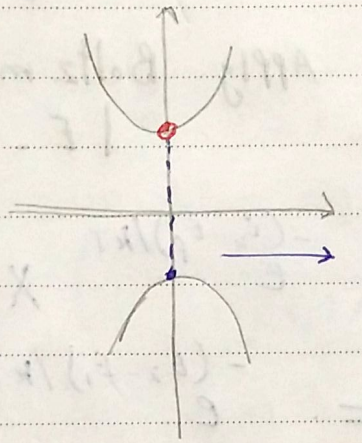
Probability for radiation of Phonon is large for indirect semi conductor → multiple Phonon



indirect

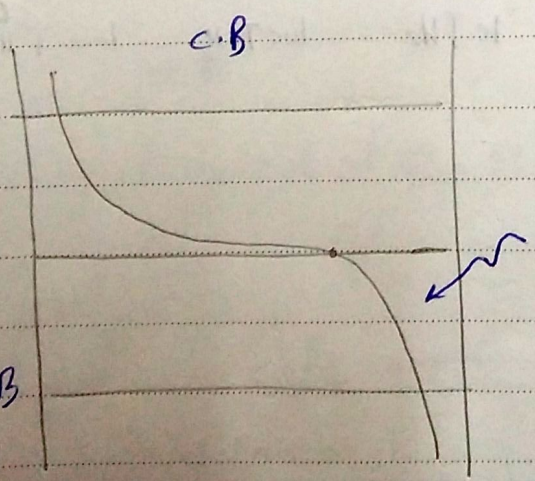


direct

Probability of Absorption & emission :

1)- Thermal Equilibrium :

Probability of finding electron is defined one fermi function



$$f(E) = 1/\left(e^{(E-E_f)/kt} + 1\right)$$

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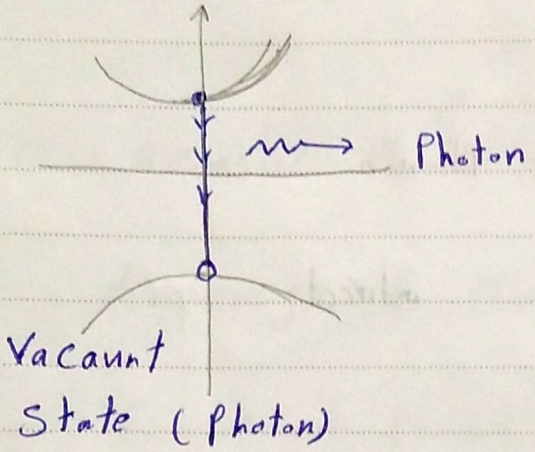
$P_{emission} = ?$



$$P_e = f(E_2) \cdot [1 - f(E_1)]$$

$$= \frac{1}{e^{(E_2-E_f)/kT} + 1} \cdot \left[1 - \frac{1}{e^{(E_1-E_f)/kT} + 1}\right]$$

$$= \left[\frac{1}{e^{(E_2-E_f)/kT} + 1}\right] \left[\frac{e^{(E_1-E_f)/kT}}{e^{(E_1-E_f)/kT} + 1}\right]$$

Apply Boltzman's Approx

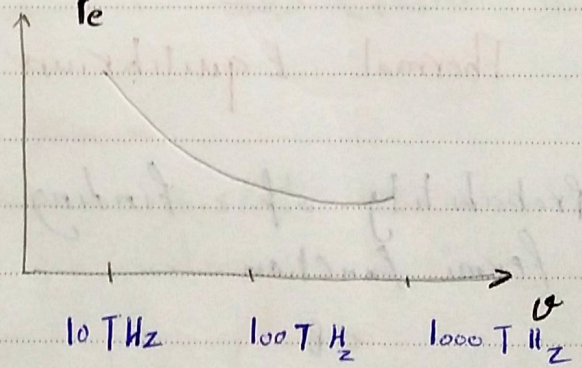
$$|E - E_f| >> kT$$

$$\Rightarrow P_e = e^{-(E_2-E_f)/kT} \times e^{(E_1-E_f)/kT}$$

$$= e^{-(E_2-E_1)/kT}$$

$$P_e = e^{-h\nu/kT} \simeq \text{Zero} \qquad T = 300\ k = \text{Const}$$

$h\nu \rightarrow$ 0.025 mev



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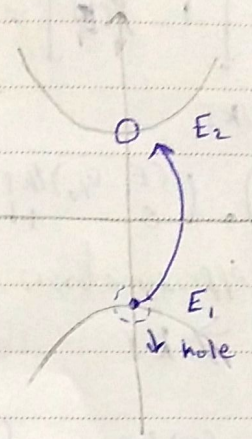
$P_{absorption}$ =



electron E_1 exists in V.B

Vacant state E_2 exists in C.B ⇝

$$P_{ab} = f(E_1)\,[1 - f(E_2)]$$

$$= \frac{1}{e^{(E_1-E_f)/kT}+1}\left(1 - \frac{1}{e^{(E_2-E_f)/kT}+1}\right)$$

$$= \left(\frac{1}{e^{(E_1-E_f)/kT}+1}\right)\left(\frac{e^{(E_2-E_f)/kT}}{e^{(E_2-E_f)/kT}+1}\right)$$

$$|E - E_f| \gg kT$$

$$P_{ab} \simeq 1$$

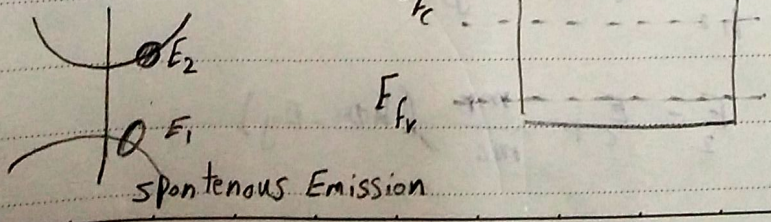
$$P_{abs} > P_e$$

Lec (13)

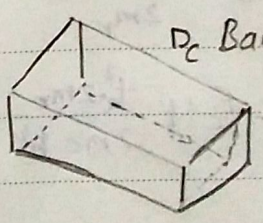
At thermal equilibrium

$$P_e = e^{-h\omega/kT}$$

The probability of emission at Quasi equilibrium



Spontenous Emission



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$$P_e = f_c(E_2)\left[1 - f_v(E_1)\right] = \frac{1}{e^{(E_2-E_{Fc})/kT}+1} \times \left[1 - \frac{1}{e^{(E_1-E_{Fv})/kT}+1}\right]$$

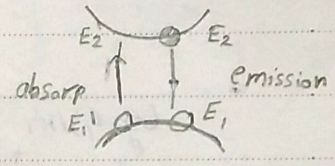
$$= \frac{1 \cdot e^{(E_1-E_{Fv})/kT}}{\left(e^{(E_2-E_{Fc})/kT}+1\right)\cdot\left(e^{(E_1-E_{Fv})/kT}+1\right)}$$

Apply Boltzman Approximation:

$(E_2 - E_{Fc}) \gg kT$ & $|(E_1 - E_{Fv})| \gg kT$

$$P_e = e^{-(E_2-E_{Fc})/kT} \cdot e^{(E_{Fc}-E_{Fv})/kT} = e^{-(E_2-E_1)/kT} \cdot e^{(E_{Fc}-E_{Fv})/kT}$$

$$P_e = e^{-h\nu/kT} \cdot e^{(E_{Fc}-E_{Fv})/kT}$$



Rate of spentenous Emission →

$R_{sp} = \frac{1}{\tau_r} \cdot \rho(\nu) \cdot P_e$ = No of emitted photon Per unit time Per unit Volume Per unit energy

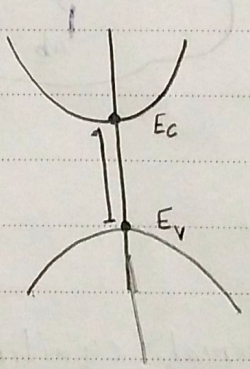
$\rho(\nu)$ = optical join density & τ_r time of recombination

↓ no. of (emitted or absorped photon) Per unit Volume Per unit energy

$\rho(\nu)$

$$E_2 = E_c + \frac{\hbar^2 k^2}{2m_c} \quad , \text{①}$$

$$E_1 = E_v + \frac{\hbar^2 k^2}{2m_v} \quad \text{②}$$



② - ① ⟹

$$h\nu = E_g + \frac{\hbar^2 k^2}{2}\left(\frac{1}{m_c} + \frac{1}{m_v}\right) = \frac{1}{m_r}$$

$$h\nu = E_g + \frac{\hbar^2 k^2}{2m_r}$$

$$k^2 = \frac{2m_r}{\hbar^2}(h\nu - E_g)$$

$$E_2 = E_c + \frac{\hbar^2 \cdot 2m_r}{2m_c \hbar^2}(h\nu - E_g)$$

$$E_2 = E_c + \frac{m_r}{m_c}(h\nu - E_g)$$

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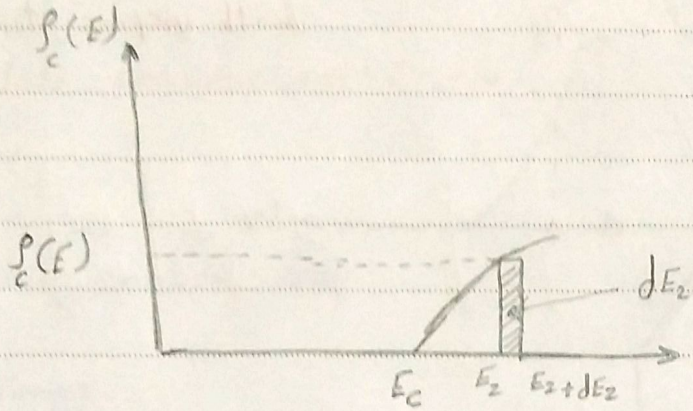
No of allowed state per unit volume $(E_2 \longrightarrow E_2 + dE_2)$



$$\rho(E_2)\,dE_2 = \rho(\nu)\,.\,d\nu$$

$$\rho(\nu) = \rho_c(E_2)\,.\frac{dE_2}{d\nu}$$

$$\rho(\nu) = \frac{1}{2\pi^2}\left(\frac{2mc}{\hbar^2}\right)^{3/2}(E_2-E_c)^{\frac{1}{2}}\,.\,\frac{m_r}{mc}\,h$$

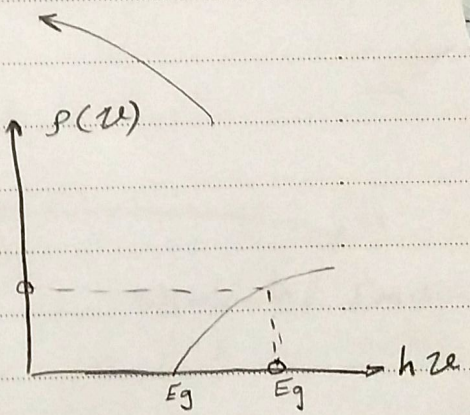
$$(E_2-E_c) = \frac{m_r}{m_c}(h\nu - E_g)$$

$$\rho(\nu) = \frac{1}{\pi\hbar^2}(2m_r)^{3/2}\,.\,(h\nu - E_g)^{\frac{1}{2}}$$

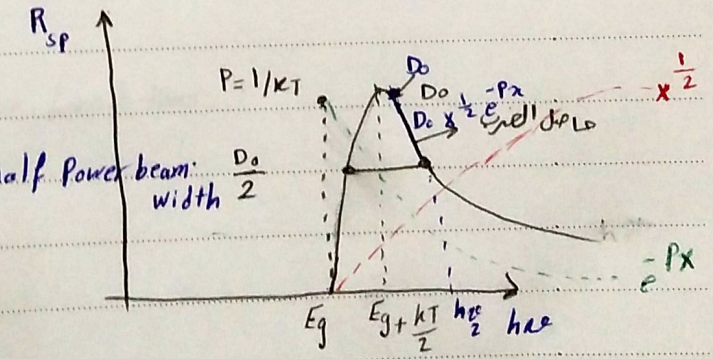
$$R_{sp} = \frac{1}{\tau_r \pi\hbar^2}(2m_r)^{\frac{3}{2}}\,.\,(h\nu - E_g)^{\frac{1}{2}}\,e^{-h\nu/kT}$$

$$= \frac{1}{\tau_r \pi\hbar^2}(2m_r)^{3/2}\,e^{-E_g/kT}\left[(h\nu - E_g)^{\frac{1}{2}}\,.\,e^{-(h\nu - E_g)/kT}\right]$$

x $\qquad$ $\beta = \frac{1}{kT}$



$$R_{sp} = D_o\,x^{\frac{1}{2}}\,e^{-\beta x}$$



$$\frac{dR_{sp}}{dh\nu} = 0 \Longrightarrow [h\nu]_{peach\ value}$$

$$\Delta f = 1{,}45\ KT\ f_p^2$$

$$\Delta\nu = 1{,}45\ KT\ e$$

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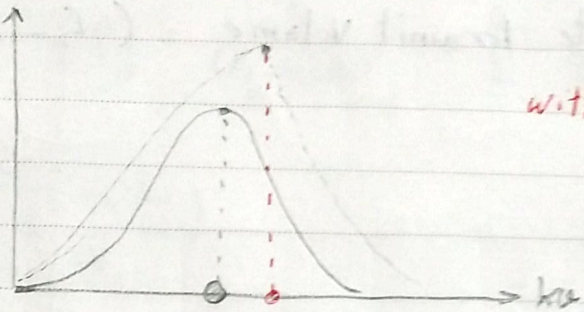
Comp msc given reaction draw



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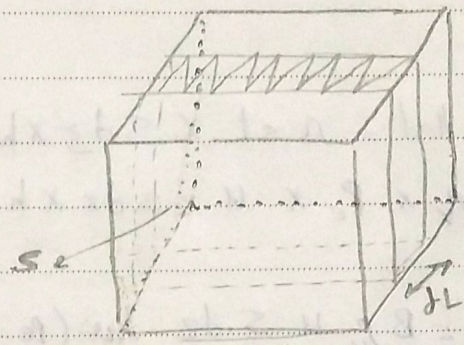
Lec (14)

Stimulate Emission Amplification :

S : Cross section Area



$$\text{Power} = \frac{\text{Energy}}{\text{unit time}}$$

$$\text{Irradiance} = \frac{\text{Power}}{\text{unit Area}} = I$$

Energy density u = energy / unit volume

Amplifire : $\longrightarrow I^{in} \rightarrow \boxed{\text{Amp}} \rightarrow I^{out}$, $I^{out} > I^{in}$

$\longrightarrow z$

Amplifire

stimulation

① Absorption

rate of Absorption = R_{ab}

$R_{ab} = B \times \rho_\nu \times P_{abs} \times V$

R_{ab} = no of absorped Photon / unit Volume / unit time

$$B = \frac{v^3}{8\pi h z_r u^3}$$

v = speed of wave inside material

u = frequency of incidient wave

Stimulated Emission

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No of absorped photon in $S.dz = B\rho_\nu P_{abs} u.S.dz$

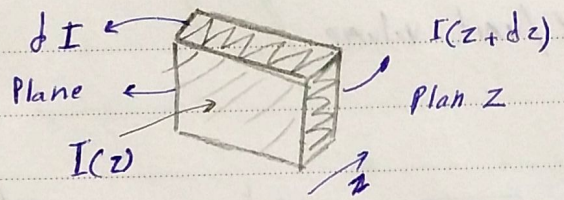
inergy absorped is $S.dz = B\rho_\nu P_{abs}.u.S.dz.h\nu$

Illy

Energy Emitted $= n\,st \times S.dz \times h\nu$

$= B \times \rho_\nu \times P_e \times u \times S dz \times h\nu$

Net energy $= B\rho_\nu u\, S.dz\, h\nu (P_e - P_{ab})$ /unit time



$dI \times S = B\rho_\nu u S dz\, h\nu (P_e - P_{ab})$

$\frac{dI}{dz} = B\rho_\nu u\, h\nu (P_e - P_{ab})$

$u = \frac{I}{v}$

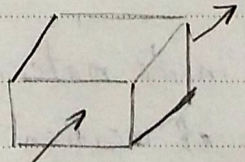
$\frac{dI(z)}{d(z)} = \frac{B\rho_\nu h\nu}{v} (P_e - P_{ab}) I(z)$

$v \rightarrow$ speed

γ

$\frac{dI(z)}{d(z)} = \gamma I(z) \Rightarrow I(z) = I_o e^{\gamma z}$

$v = \frac{c}{n}$



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γ

$\gamma = +ve$ — Amplifire — γ = Gain

$\gamma = -ve$ — Attenuation — γ = loss

$$\gamma = \frac{B \rho_v h\nu}{v} (P_e - P_{abs})$$

$$\rho_v = \frac{1}{\pi \hbar^2} (2m_r)^{\frac{3}{2}} (h\nu - E_g)^{\frac{1}{2}}$$

$h\nu > E_g$

$$B = \frac{c^3}{8\pi h \nu^3}$$

Equasi Equilibrium (Bump) $P_e > P_{abs}$

two fermi level E_{fc}, E_{fv}

two : function

$$P_e = f_c(E_2) \times [1 - f_v(E_1)] = \frac{1}{e^{(E_2 - E_{fc})/kT} + 1} \times \frac{e^{(E_1 - E_{fv})/kT}}{e^{(E_2 - E_{fv})/kT} + 1}$$

$$P_{abs} = f_v(E_1) \times [1 - f_c(E_2)] = \frac{1}{e^{(E_1 - E_{fv})/kT} + 1} \times \frac{e^{(E_2 - E_{fc})/kT}}{e^{(E_2 - E_{fc})/kT} + 1}$$

$P_e > P_{ab}$

$(E_1 - E_{fv}) > E_2 - E_{fc}$

$(E_2 - E_1) < (E_{fc} - E_{fv})$

$E_g < h\nu < (E_{fc} - E_{fv})$ $\Rightarrow$ $\frac{E_g}{h} < \nu < \left(\frac{E_{fc} - E_{fv}}{h}\right)$

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$$P_e - P_{ab} = f_c(E_2)\,(1 - f(E_1)) - f_v(E_1)\,(1 - f_c(E_2))$$

$$P_e - P_{ab} = f_c(E_2) - f_v(E_1)$$

$$\gamma = \frac{v^3}{8\pi h v^3} \times \frac{1}{\pi h^2} (2mr)^{\frac{3}{2}} \cdot \frac{hv}{v} (hv - E_g)^{\frac{1}{2}} \left(f_c(E_2) - f_v(E_1)\right)$$

$$= \frac{v^2 (2mr)^{\frac{3}{2}}}{2h^2 v^2} (hv - E_g)^{\frac{1}{2}} \left(f_c(E_2) - f_v(E_1)\right)$$

$$\gamma = \frac{(c/n)^2}{2\bar{c}_r} \cdot \frac{(2mr)^{\frac{3}{2}}}{(hv)^2} (hv - E_g)^{\frac{1}{2}} \cdot \left(f_c(E_2) - f_v(E_1)\right)$$

EX: at $T = 0K^0$

a) - Thermal Equilibrium :

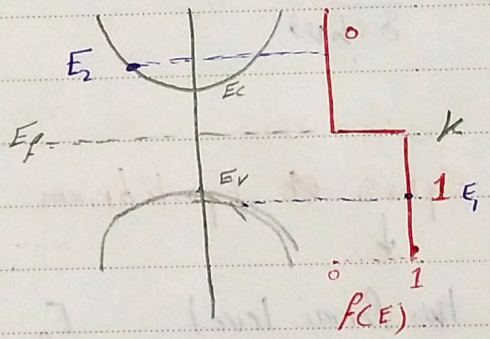
$$f(E) = \frac{1}{e^{(E-E_c)/kT} + 1}$$

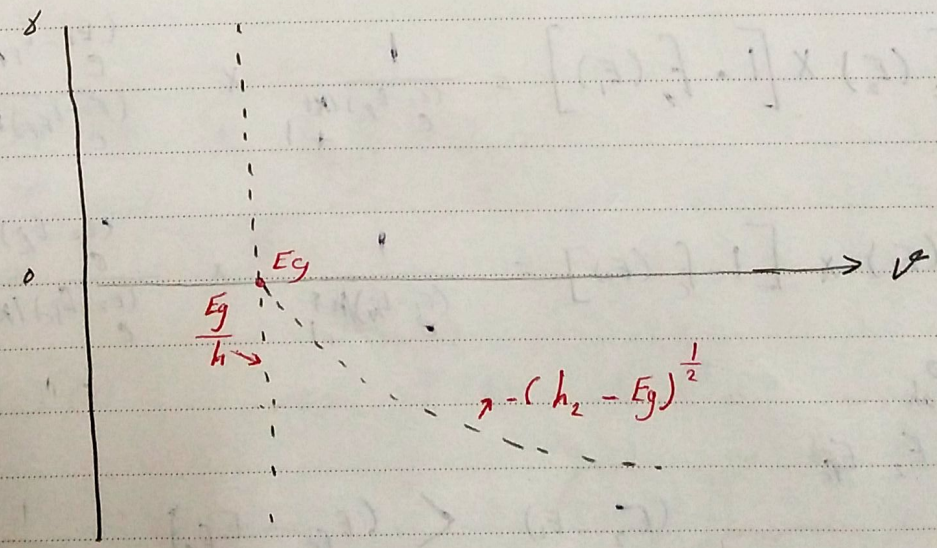
$f(E_2)$ = Zero

$f(E_1) = 1$

$f(E_2) - f(E_1) = -1$

γ = -ve





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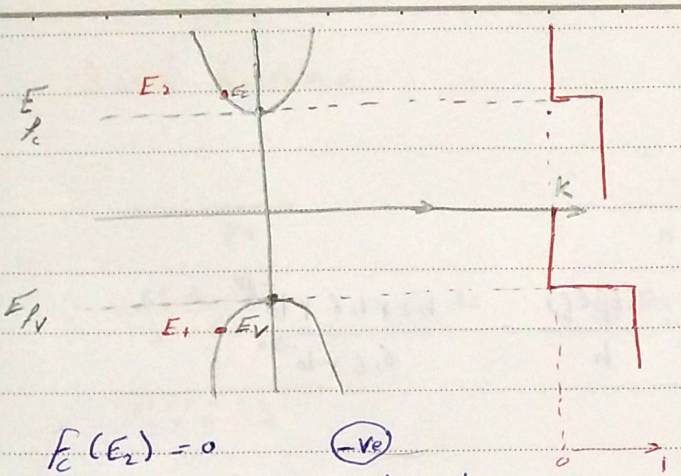


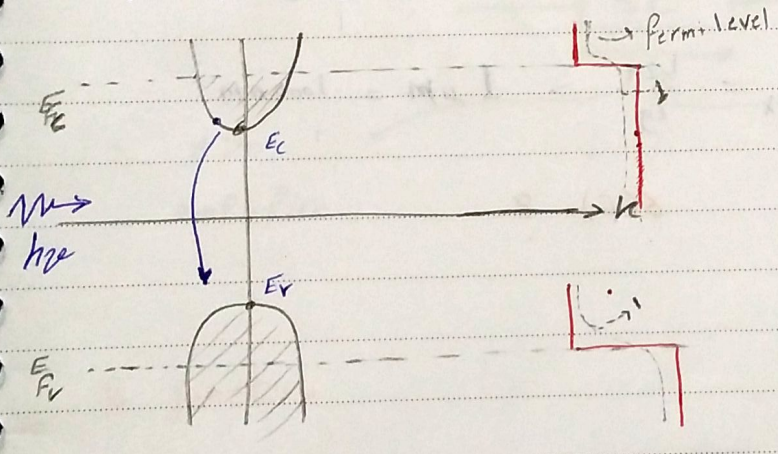
$f_c(E_2) = 0$

$f_v(E_1) = 0$

(-ve) attenuator

Quasi equilibrium

$(E_{Fc} - E_{Fv}) > E_g$



$f_c(E_2) = 1$

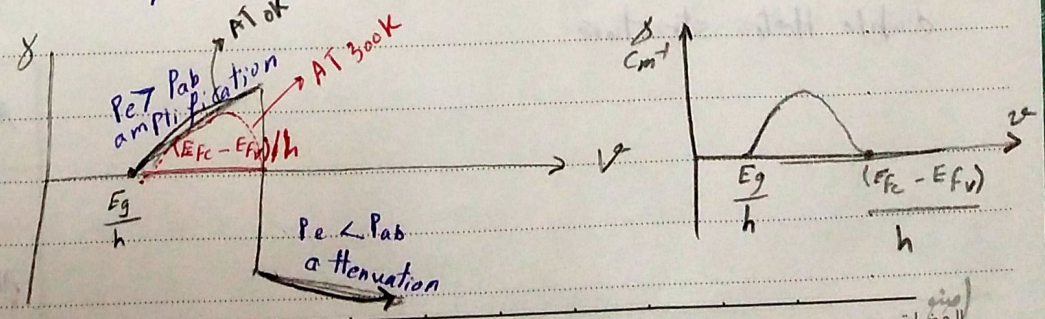
$f_v(E_1) = 0$

$f_c(E_2) - f_v(E_1) = +1$

γ = +ve

amplification

amplification



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EX:

$E_g = 1\,eV$

$E_{fc} - E_{fv} \simeq 1,2$

* $\frac{E_g}{h} = \frac{1 \times 1,6 \times 10^{-19}}{6,6 \times 10^{-34}} \simeq 0,25 \times 10^{15}\,Hz$, $\frac{(E_{Fc} - E_{fv})}{h} = \frac{1,2 \times 1,6 \times 10^{-19}}{6,6 \times 10^{-34}}$

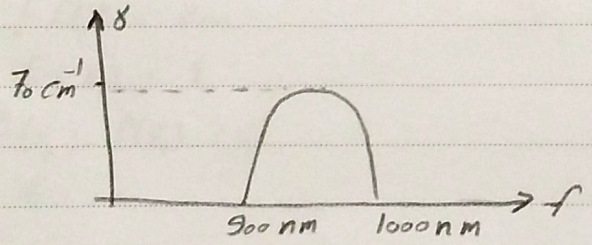
$\Rightarrow$ range of operation (BW)

250 T Hz $\longrightarrow$

(Lec 15) 30

Ex: give semi conductor Amplifire made of $I_{n}GAP$ with $Eg = 1,24\,eV$
Peak Cofficent gain = $70\,cm^{-1}$ & $Bw = 100\,nm$
Draw the variation of the amplification coff with wavelength

Sol: $Eg = 1,24\,eV \Rightarrow f_{max} = \frac{1,24}{Eg} = 1\,\mu m = 1000\,nm$

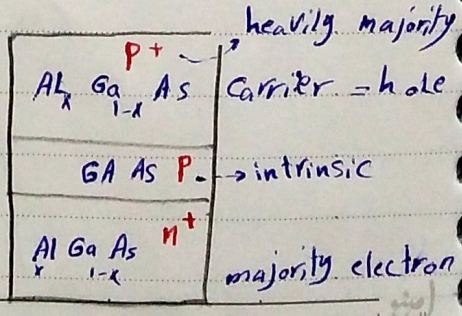


$\gamma(f)$?

$\gamma > 0$ & $P_e > P_{abs}$

$(E_{fc} - E_{fv}) > Eg$

Main Structure:
double Hetro structure



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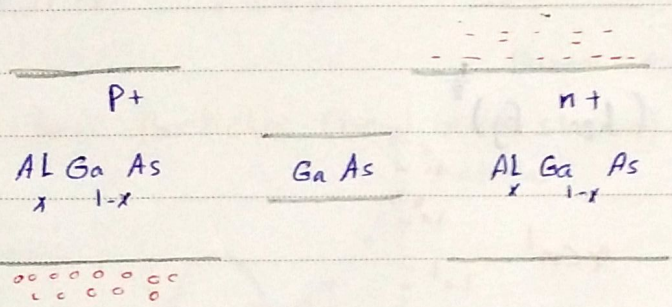
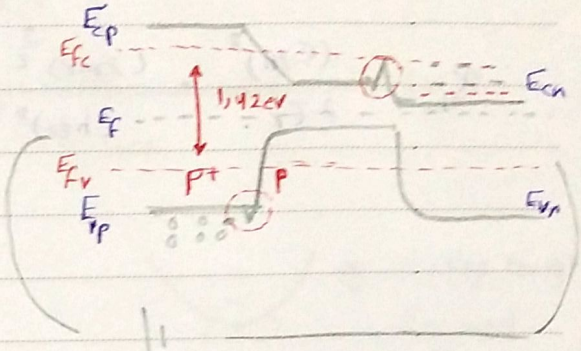
Band diagrame

steady state.



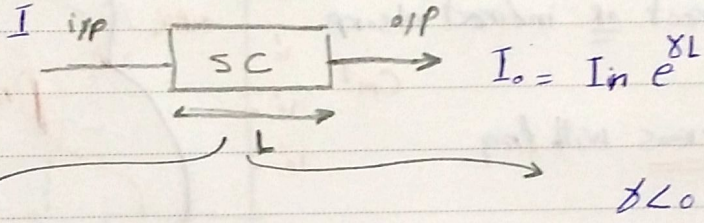


Assume $X = 0,1$

$Eg = 1,5$ ev

$Eg = 1,42$ eV

Attenuation :



$I_o = I_{in}\, e^{\gamma L}$

$\gamma > 0$

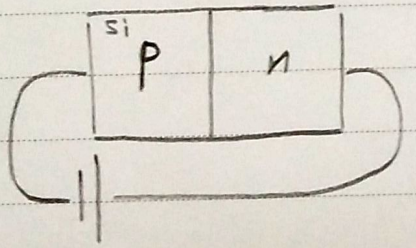
amplifire

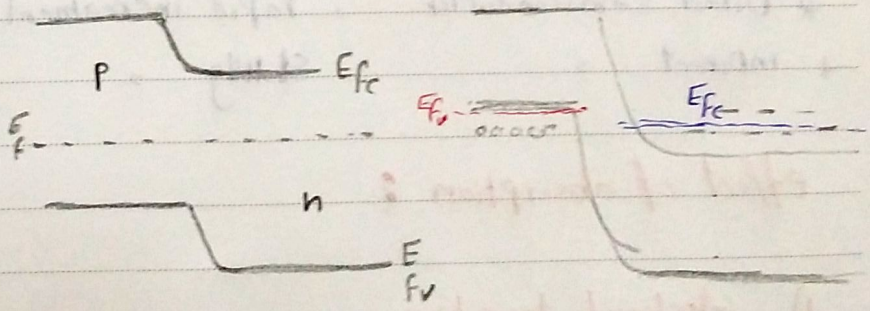
$\gamma < 0$

$P_e < P_{ab}$

$P_e - P_{abs} = (f_c(E_2) - f_v(E_1)) < 0$

Pn junction





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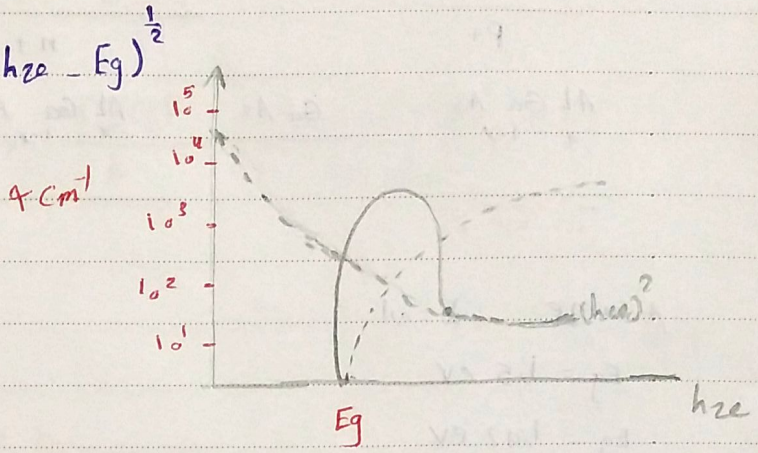
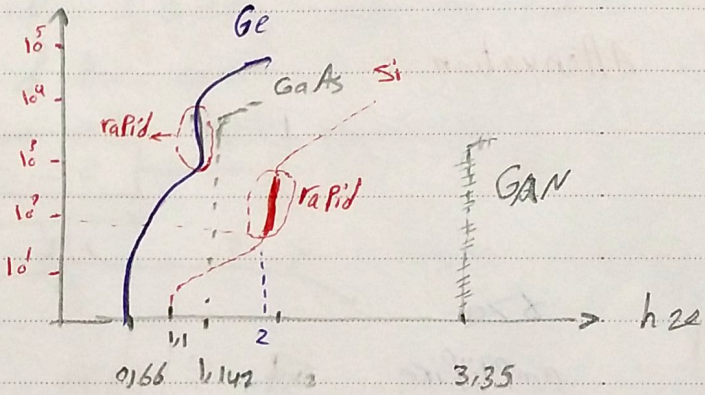
Absorption Spectrum :

$\gamma = -\alpha_{abs}$

$$\alpha_{abs} = \frac{(C/n)^2}{2\tau r} \cdot \frac{(2mr)^{\frac{3}{2}}}{(h\nu_0)^2} \cdot (h\nu_0 - Eg)^{\frac{1}{2}}$$



typical Absorption spectrum :



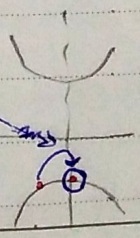
* Any material Direct or indirect absorp
* Absorption increas with freq
* Curves Consider indirect band gap

$$\alpha(cm^{-1}) = (K_0 + K_1 T)(h\nu_0 - Eg)^2$$

* Direct semiconductor , rapid increament
* inDirect = , Slowly =

effect of absorption ?

1) interband transition
electron excited from V.B to C.B
2) intraband transition :
electron excited in the same band (from position to another)



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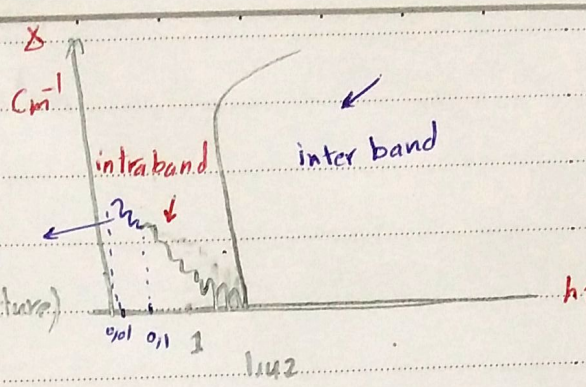
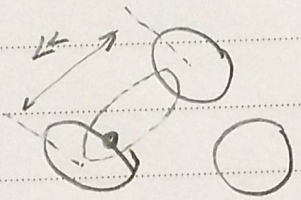
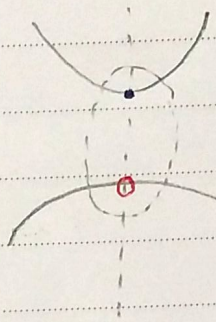
3.) - Phanome

0,01 eV ⟶ 0,1 eV



4) Excitonic Particles (report in nano structure) material





Eg = Binding energy

= (1a mer)

↙

attraction

Columbs force

Excited electron hole pair

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